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A Study of the Adequacy of Quasi-Geostrophic Dynamics for Modeling the Effect of Frontal Cyclones on the Larger Scale Flow

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A Study of the Adequacy of Quasi-Geostrophic Dynamics for Modeling the Effect of Frontal Cyclones on the Larger Scale Flow

Abstract

The purpose of this work is to study the evolution of individual cyclone waves in order to see how well quasi-geostrophic (QG) dynamics can simulate the behavior of primitive equations (PE) dynamics. This work is an extension of a similar study (Mudrick, 1982); emphasis is placed here on adding a frontal zone and other more diverse features to the basic states used.

In addition, sets of PE integrations, with and without friction, are used to study the formation of surface occluded fronts within the evolving cyclones.

Results of the study are summarized at the beginning of this report.

Papers published under this grant:

Mudrick, S.E., 1987: Numerical Simulation of Polar Lows and Comma Clouds Using Simple Dry Models. Mon. Wea. Rev. 115, in press.

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Summary of Results

A major thrust of this study was the attempt to add frontal zones to the basic states used for PE/QG comparisons of evolving cyclone waves. The attempt was only partially successful. Three different situations were used within which frontal zones were present; only in one case did a frontal wave cyclone form in the desired manner. Other basic states, however, possessing a greater diversity from those basic states used in Mudrick (1982), of which this study is an extension, were used here.

With respect to the frictionless PE/QG comparisons: three out of four additional basic states provided good results. These results are similar to those described in Mudrick (1982).

1) The PE cyclone waves stabilize the lower troposphere while the QG model evolutions cannot.

2) Both PE and QG cyclones evolve through life cycles as seen in the gross energetics, with the QG cycles generally lasting longer.

3) The QG life cycle averaged eddy heat fluxes are similar to the corresponding PE fluxes; the heat fluxes are more similar than are the PE vs QG momentum fluxes.

There is more diversity in the PE/QG comparisons than was found in the Mudrick (1982) study. The QG fluxes are weaker than the corresponding PE fluxes in one case, but are stronger than the PE fluxes in two other cases (much stronger in one case). In Mudrick (1982) they were weaker than the PE fluxes.

These results suggest, along with the findings of MacVean and James (1986), that our confidence in the ability of the QG dynamics to simulate the PE dynamics should be reduced, compared to the findings of the Mudrick (1982) study.

With respect to the attempt to model surface occluded frontogenesis within evolving cyclone waves, using PE models with and without friction: the results suggest that the forming or completely formed cold front does "catch up" to the warm front to form a narrow occluded region, as in the classical occluded front model, but that as this occurs the northern end of the cold front weakens.

Acknowledgements

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1. Introduction

As written in the proposal for this project, the objectives of the research are twofold:

1) To test the validity of quasi-geostrophic dynamics, compared to primitive equation dynamics, for modeling the effect of cyclone waves on the larger scale flow, and
2) To study the formation of frontal cyclones and the dynamics of occluded frontogenesis.

This project is an outgrowth of an NSF project which is summarized in Mudrick (1982), hereafter known as M82. (All Mudrick papers referenced herein will be referred to as M with the appropriate date following.) In that project, parallel channel model primitive equation (PE) and quasi-geostrophic (QG) integrations were made for five different basic states, upon which small disturbances were superimposed. The idea, expressed in objective 1) above, was to see how well the QG integrations could simulate the PE results with emphasis placed upon the changes in the zonally averaged fields at the end of the disturbance life cycles. For the five cases, the QG model produced changes in the zonally averaged buoyancy to similar to the PE model, but the differences were judged to be significant. The main difference was that the PE disturbances stabilized the lower atmosphere while the QG average lapse rate is constrained to be constant in time. (Buoyancy is dynamically similar to potential temperature. The models will be referenced below). The PE and QG zonally averaged eddy heat and momentum fluxes were averaged over the disturbance life cycles and were compared. The heat fluxes were more similar than the momentum fluxes. The M82 findings suggested "the feasibility of basing parameterizations of cyclone waves on the

quasi-geostrophic eddy heat fluxes," but it was acknowledged that the task would be difficult and several caveats were included as to the ability of QG dynamics to simulate PE cyclone wave evolution.
A similar study, parallel to the M82 work was reported by MacVean and James (1986), using PE and QG spherical, spectral models. Their models were adiabatic, except for diffusion operators, as are the models used in M82. They studied several cases, comparing PE and QG life cycles. Their results are similar to those in M82 but their conclusions concerning the ability of the QG dynamics to simulate the PE dynamics were less optimistic. They emphasized the momentum fluxes rather than the heat fluxes which were emphasized in M82. Since the momentum fluxes become larger and the heat fluxes weaken toward the latter part of the life cycle and since (in both M82 and MacVean and James, 1986) the momentum fluxes can be significantly different for the PE and QG models, varying irregularly from case to case, they concluded "the use of QG rather than PE dynamics to parametarize the total effects of baroclinic waves in low resolution long term integrations would lead to significantly different model climatologies." Thus the two studies found similar results but placed different emphases on them.

Both studies mentioned above used fairly simple, smooth basic states. How much different would the result be if a realistic frontal zone were present in the basic state? Indeed, the addition of a frontal zone was one of the main purposes in carrying out this study, as evidenced in the title. The chief goal of the project was to carry out objective 1) above for basic states within which frontal zones were present, the idea being that frontal cyclones would develop in both the PE and QG models.

It was also realized that surface friction should be included in both models if surface fronts were to be present initially. Adding friction to the PE model was straightforward; it had been done for some of my Ph.D. work, but due to the he nature of the QG model and due to time constraints, friction was never added to the QG model. Thus all PE/QG comparisons discussed in this report (and all such comparisons in M82) involve frictionless cases.

Friction was added to the PE model for various runs. This increased the realism of the occluded region as the cyclone matured. The formation of the "occluded front" within a cyclone was studied, based on these friction runs, allowing objective 2) to be carried out.

This report will be organized in a manner similar to M82. Details of the model and the initial states discussed here will be referenced and results will then be presented.

2. Model details

The PE and QG models used here are restricted to dry, hydrostatic, adiabatic motion and the Boussinesq approximation is made. The atmosphere is simulated by an east-west re-entrant channel with rigid horizontal and vertical boundaries, located on a mid-latitude beta plane with no orographic features. For the PE/QG comparison cases the flow is inviscid except for short wave filters and the damping implicit in the Lax-Wendroff-like second order accurate scheme. Details of the PE and QG equations and models are referenced in M82; details of the friction in the PE model are discussed in M87. The PE model contains a convective adjustment scheme designed to keep the model atmosphere from having regions of lapse rate greater than dry adiabatic; the scheme is discussed in M76.

3. Initial states

All the basic states used here are similar in structure to those discussed in M82, section 4. All possess the $\sin^2 y$ structure mentioned there. Differences will be discussed in the Results section below. Tables 1 and 2 present data for basic state I-N(0), discussed in M82 (and referred to as run 2 there), as well as for three other situations: I-N(0)FZ, the I-N(0) case with an initial E-W surface frontal zone present; PL/CC, a case designed to simulate the region within which "polar lows" and "comma clouds" tend to form (this case is the basis for M87) and 2-Wave, a basic state similar to I-N(0) but with two small amplitude, normal mode disturbances present initially, a long wave and two short waves. These cases will be discussed in detail below. Tables 1 and 2 are similar to Tables 1 and 2 of M82.

In addition to the basic states mentioned, a "strong front, strong jet" case was used for PE /QG comparison integrations. This basic state was designed to simulate a realistic, strong jet with an associated frontal zone extending throughout the depth of the troposphere. This case, while not appearing in the tables, will be discussed in the Results section.

The initial perturbations were found and were added to the basic states to form the initial conditions for the PE and QG runs as referenced in M82. All the runs discussed here, unless indicated, used the INT filter described in section 6 of M82.

4. Energetics

Section 5 of M82 describes and defines the energetics expressions used here. As in that paper, the QG energetics forms are used to describe both the PE and QG output, although they are formally valid only for the QG model. We will discuss the zonal available potential energy ZAPE, the zonal kinetic energy ZKE, and the eddy energy EE made up of the eddy available potential energy EAPE plus the eddy kinetic energy EKE.

5. Results

A summary of the results of this project appears at the beginning of this report as well as at the end of this section. This section will be organized as follows: The first portion will be concerned with the PE/QG comparisons. This portion will first discuss situations where surface fronts were present when the cyclones began to evolve. Then other basic states will be discussed. The next portion will discuss PE runs only and will deal with occluded frontogenesis. The results will be summarized and implications will be discussed.

A. PE/QG Comparisons

There are four basic states that will be discussed here; in addition the I-N(0) case from M82 will be referenced. Tables 1 and 2 in this report give details of these cases; the one case not in the tables, the "strong front, strong jet" case, will be described below.

I. Adding fronts to the basic state.

We will first discuss attempts to model "frontal wave cyclones", i.e. those cyclones evolving on a pre-existing frontal zone. This was one of the major aims of the project. Three cases will be described: the "weak front" case I-N(0)FZ, the "strong front, strong jet" case and the "2-wave" case.

a. The weak front case, I-N(0)FZ

This was the first attempt at adding a frontal zone to the basic state. The hope was that, with the initial frontal zone present, a cyclone would form on the front and the evolution of a "frontal cyclone" would be modeled. The initial front was quite weak, as discussed below; this was done so that QG dynamics could still be argued as being valid for a study of the basic state, since a linear QG model called 2DINIT is used to determine the structure of the fastest growing normal mode. As the cyclone evolved, the front tended to weaken in the vicinity of the low center so that the evolution of the low was quite similar to the cyclone in the no initial front case I-N(0). Effectively, the cyclone did not "feel" the presence of the front as it evolved but due to the increased stability in the frontal region, the cyclone growth rate was decreased. While a frontal cyclone was thus not modeled in this case, the results are still of interest and are now described.

Basic state I-N(0)FZ is a modification of basic state I-N(0); a weak E-W oriented surface frontal zone was added. This involved changing, by hand input, buoyancy (b) values in the lowest levels (k=1 to 3) in the basic state. The modifications were made to create a sloping, stable region with an enhanced N-S b gradient within the region. After the b's were modified, the pressure field p was obtained via $b = \partial p/\partial z$, the model hydrostatic equation, by integrating downward from the known b and p values at level k = 4. For finite differences ($y=j\Delta y$, $z=k\Delta z$; y is northward, z is upward) we have

$$\frac{b_{j,k+1} + b_{j,k}}{2} = \frac{p_{j,k+1} - p_{j,k}}{\Delta z} \quad \text{or} \quad p_{j,k} = p_{j,k+1} - \frac{\Delta z}{2}(b_{j,k}+b_{j,k+1}).$$

Program 2DINIT, the linear, two dimensional quasi-geostrophic model that determines the structure and growth rate of the most rapidly growing normal mode, then proceeds as before, using the $p_{j,k}$ field.

Without the front present, the maximum N-S b gradient at k=1, dimensionalized, is 1.16°C/100km and the entire baroclinic zone extends N-S over about 10 grid distances (1500km). With the front present, the maximum value is 1.64°C/100km and the front extends N-S over four grid distances (600km). The front is seen to be quite weak.

The front is added by tightening the b gradient on the cold side of the baroclinic zone in the lowest 3 levels, but not reducing the minimum b value for any level (level 1 more so than level 2, level 2 more so than level 3). Thus, the average stability $N^2=\partial\bar{b}/\partial z$ is increased for the lower levels of the channel ($\bar{b}$ is the y averaged b). This would reduce the growth rate in the quasi-geostrophic 2DINIT model, in addition to the reduction due to the relatively stable area associated with the frontal zone. $N^2(z)$ was thus set equal to the values for the no front case by adjusting $\bar{b}$ for the lowest 3 levels.

The front added in this way consisted of a sloping, stable zone with enhanced positive relative vorticity on the warm side of the front, as expected. The reduction of $\partial b/\partial y$ north of the cold side of the front produced a reduction of $\partial u/\partial z$ in the same area (u is the zonal wind component), due to the thermal wind constraint; since p was gotten by integrating downward from level 4, u was unchanged above level 4 and u has increased westerly values near the surface, north of the frontal zone. Thus, a second region of positive relative vorticity is present north of the cold front. This region did not cause any major problems in subsequent integrations. Table 1 shows that the minimum Richardson number increases in the frontal zone, compared to the no front case.

The result of the changes was that for the 3600km length channel used, the structure and growth rate of the most unstable normal mode changed significantly from I-N(0). For I-N(0)FZ the growth rate was decreased, the doubling time increased to 1.47 days as opposed to 0.97days for the unmodified basic state (see Table 2). Both perturbations grow via the mixed mode process, both ZAPE and ZKE being converted to EE. The no front disturbance has its maximum disturbance amplitude at jet level and is more or less symmetric around a vertical axis beneath the jet. The front disturbance has its maximum amplitude at the bottom, on the front, and the maximum slopes upward and northward toward the jet core. The reduced growth rate for the front case is reasonable since the region of several grid distances across has significantly greater stability due to the presence of the front. In the atmosphere, a front is perhaps 100km or less in thickness; here it is greater than 600km. Having gotten the normal mode structure, the disturbance was added to the basic state, and the initial data were "balanced" (see M74, p873). The INT filter and initial disturbance amplitude of 10% were used, similar to run 2 in M82. The PE run was made in this manner; a QG run was also made, similar to the QG no front run (run 2) in M82. Both runs were carried out to eleven days.

In addition to the above non friction runs, the PE model was also integrated with two types of friction, a surface stress only and a more complete vertical diffusion form of friction. These results will be discussed later in the "surface occluded frontogenesis" section.

A comparison of the PE and QG front cases is somewhat similar to the comparison of the PE and QG cases of run 2 discussed in M82, with some notable differences as discussed below. A more detailed discussion is planned for a forthcoming paper.

The energetics behavior for the I-N(0) and I-N(0)FZ runs is shown in Table 3. Note they are similar, except that the PE front run takes longer to reach a maximum in EE and to complete a life cycle (6¼ days, ∿10 days) than does the PE no front run (4.6 days, 8 days). However, the QG front run is more similar to the QG no front run (6¼ days, ∿14 days for the front case, 6.4 days, 14 days for the no front case). It appears that, with respect to the gross energetics behavior, the QG run is less affected by the presence of the front than is the PE run, which is significantly stabilized. For both front and no front cases the PE disturbances evolve more quickly than do the QG disturbances. This is probably due to the fact that the PE model stabilizes the buoyancy field (relative cooling at the channel bottom and warming above) as the disturbance evolves while the QG model is constrained to have an unchanging stability. Thus, the PE buoyancy stabilizes with time and the perturbation completes its life cycle sooner than for the QG case.

With respect to the zonally and time averaged fluxes of heat and momentum (time averaged over the respective life cycles) Table 4 presents data for the I-N(0) and I-N(0)FZ cases. Consider first the horizontal heat flux $\overline{b'v'}^{xt}$. All PE and QG runs, no front and front, have northward fluxes with the maximum at the channel bottom (level k=1). All have a weaker, southward flux in the lower stratosphere (level k=8); due to the rigid top this may be an unrealistic feature. The PE fluxes are stronger than the QG fluxes in both the front and no front cases. Both the PE and QG fluxes tilt northward with height, the PE more so, for the front case, whereas for the no front case, the PE has a slight northward tilt with the QG being vertical and nearly symmetric about a vertical axis beneath the jet core. Thus, the front case removes the symmetry from the QG run. In general the QG flux is more similar to the PE flux for the front case than for the no front case.

Next consider the horizontal time averaged momentum flux $\overline{u'v'}^{xt}$. In general, the momentum fluxes tend to be less similar than are the heat fluxes, as pointed out by M82 and by MacVean and James (1986). The PE fluxes for the front and no front cases are qualitatively quite similar. Both are directed southward. Both have maxima at levels 1 and 7, with the upper level maximum being three gridpoints southward of the lower level maximum. The maxima are at the same location for both cases. The front case has the absolute maximum at level 7 while the no front case has it at k=1. The QG flux for the front case is qualitatively somewhat similar, albeit less than half as strong, with a nearly all southward flux possessing two maxima at levels 1 and 7. The upper level maximum is one gridpoint southward of the lower level maximum. There is a region of weaker northward flux north of the jet at level 9 near the top.

The QG momentum flux for the no front case is quite different than the PE no front flux. This QG flux is roughly symmetric about a vertical axis beneath the zonally averaged jet core. There is a southward directed maximum south of the jet at level 7, similar to the other cases, but there is a northward directed maximum at level 1, below this. No other case has a northward directed momentum flux at level 1. North of the vertical axis there is a northward maximum at level 9 and a weak southward directed maximum at level 4. Both QG fluxes have maxima weaker than their PE counterparts. For the front case, the PE flux maximum is over twice as strong as the QG maximum; for the no front the ratio is closer to four.

As for the heat fluxes, the presence of an initial frontal zone has removed the vertical symmetry about the jet in the QG run and more realistic results for the QG model, compared to the PE model, are noted when the fluxes are compared.

The QG results are seen to be more like the PE results for the front case, as opposed to the no front case. This is true for both the time averaged heat and momentum fluxes. It is also true for horizontal patterns of pressure and buoyancy (the "synoptic" maps not shown here) for level k=1, the lowest level in the model. Without the initial surface front the QG L and H develop in a manner similar to one another. A near "symmetry" is seen around an E-W oriented line at the center of the channel, in that the low (L) looks like the high (H). The "frontal trough" associated with the L looks like the frontal "ridge" associated with the H. This behavior can be seen in Figs 3C and 10C of M74. Also, for the QG no front case, a snake-like meander forms for the "frontal zone", similar to Fig 3D in M74, with the southward moving cold air region of similar size to the northward moving warm air region.

When the frontal zone case is considered, the QG symmetry is broken at the start. A strong H appears by day 2 compared to the weak, small L and the tightening "frontal" gradient looks more like a PE than a QG model - the cold tongue associated with the H is broad, compared to a narrow warm tongue associated with the L. By day 6 the L has grown in size similar to the H, but the frontal trough extending southward from the L is still sharper than the ridge extending northward from the H center. As time proceeds, the L and H become more similar, as in no front QG runs, but for the first 6 days or so the QG model looks quite like a PE run.

For level k=5, above the level where the front was inserted into the basic state, the QG front and no front runs are more similar. The front case is less "symmetric" about the mid-channel (in the manner discussed above) than as the no front run, but both are quite similar.

The major differences at the lower levels are due to changes in the QG potential vorticity field that come about when the front is added. The QGPV is nearly symmetric (about the E-W mid-channel line, except for the increase of the Coriolis force northward) for the no front case. The presence of the front produces the asymmetry. Since the QGPV is conserved following QG motion, the distribution of this field is of central importance in the QG integrations. A forthcoming paper is planned that will discuss this evolution in some detail; figures will be presented.

In conclusion, the presence of an initial, albeit weak surface frontal zone breaks the "symmetry" in the QG basic state. The resulting QG evolution is more similar to its PE counterpart than is the no front QG integration. Thus, it may be that with the use of more realistic initial states, compared to idealized situations used in M82, the QG model may better simulate the PE evolution. The conclusions in M may be strengthened somewhat, compared to the more pessimistic comments of MacVean and James (1986), regarding the use of QG dynamics to similate PE effects. The results from other cases to be discussed below, however, will conflict with this.

b. Strong front, strong jet case. A stable situation.

A second attempt at modeling a frontal cyclone was made by adding a strong, narrow, deep frontal zone to a basic state. The basic state for this case consisted of a strong polar front jet with an associated frontal zone extending throughout the troposphere. The situation is somewhat similar to Fig 8.2, p 198 in Palmen and Newton (1969). The main point is that a relatively strong, narrow, sloping frontal zone extends throughout the troposphere, in association with a strong, narrow, cyclonically skewed jet stream. It has been speculated that such situations can preceed explosive mid-tropospheric cyclogenesis (Shapiro, 1970).

Three full three-dimensional integrations were made for an 1800km long channel, using this basic state; two were PE integrations; one was a QG. The QG and one of the PE utilized a 5% amplitude "normal mode" disturbance, the other PE integration used a "barotropic" (i.e. no variation in z) perturbation of 5% amplitude for the initial disturbance. The "normal mode" structure was determined by a linear, QG 2-D model (2DINIT) but the structure's validity is questionable due to 1) the extreme shears and large vorticity in the basic state, probably invalidating the QG assumption used in 2DINIT, and 2) a possible error in the 2DINIT calculation for this particular situation. These runs used the JCP filter (See M82).

At any rate, the basic state proved to be stable, at least for the 1800km channel. No significant growth of the perturbations occurred, for any of the runs, out to 7 days. This result may be consistent with speculation by Palmen and Newton (1969, p 338) that " a frontal layer extending through the entire troposphere is, at least in some cases, a characteristic acquired by a cyclone during, rather than prior to, its development."

This case demonstrated that both PE and QG models could produce a "null" result for a given basic state.

c. A third attempt - a frontal cyclone - the "2-Wave" runs

The "2-Wave" basic state summarized in Tables 1 and 2 will be described below. It was run originally on the PE model, with surface stress included. After day 7, a surface low forms on a pre-existing cold front, itself having formed as a result of earlier cyclone development. This frontal cyclone develops as a short wave and associated jet streak propogate around a long wave trough at mid-levels. The frontal cyclone evolves; as it does so the front deforms and occludes. This was the first (and only) "polar front cyclone" produced during work performed for this project.

A PE run without friction, and an associated QG run were then made in an attempt to provide a frontal cyclone case for a PE/QG comparison. Unfortunately, the frontal cyclone did not form in these cases; a secondary surface low associated with the short wave trough approached the cold front from NW of it, rather than forming on the cold front. Also, the evolution and movement of this secondary low was significantly different for the PE and QG models so a comparison of the runs, at least with respect to surface development, was not made.

d. Summary of attempts to add surface fronts to the PE/QG comparisons

For the three situations described above, only the weak front case produced a PE/QG comparison, and that case showed that the QG model simulated the PE evolution even better than for the situation with no surface front present initially. The strong front, strong jet case produced a PE/QG comparison, but neither model produced a growing solution. The 2-Wave case produced a PE/QG comparison, but the interesting case of the "frontal cyclone" that appeared in the PE friction run did not reoccur in the same manner in the PE/QG comparison with no friction.

It might be possible to use as initial data the 2-Wave PE case with friction at day 6. This could be run with the PE and QG no friction models. Then the PE/QG comparison would be starting with very similar initial data and the frontal cyclone might be expected to form by day 2 or so in these runs. In order to do this, a program would need to be developed to modify the PE pressure pattern to confirm to the lateral boundaries required by the QG model; this has not been done.

Thus, based mainly on the "weak front" case, we can conclude that the addition of a frontal zone to the basic state, which otherwise is similar to the basic states studied in M82, does not adversely alter the ability of the QG model to simulate the PE evolution. In fact, for this case the QG model does a better job simulating the zonal and time averaged PE momentum and heat fluxes than in the no front basic state case.

II. Other basic states

In keeping with objective 1) in the project, basic states other than those mentioned above were run for PE/QG comparisons. These situations did not include a frontal zone in the basic state. The two cases described below both are of similar structure as that shown in Fig 1 of M82, as is I-N(0), but the differences will be emphasized. We refer to them as the "PL/CC" case and the "2-Wave" case. The former uses a cyclonically skewed jet, but the major addition is a layer of reduced stability in the lowest 3km of the channel. The basic state and details are described in M87; the basic state was chosen to similate conditions within which polar lows/comma clouds tend to develop over oceanic regions. The lowest layer simulates the effect of destabilization from below by sensible heat fluxes upon an equatorward moving polar air mass. The latter basic state is more similar to I-N(0) but it had superimposed upon it both a long wave of 5200km and 2 short waves of 2600km in the initial state; these two normal modes were such that the short waves would grow more rapidly and propogate eastward with respect to the long wave.

a. The PL/CC case

The details of the integrations are presented in M87. The tables provided in this project report give information on the parameters used. We will concentrate on the "coarse resolution" runs having 14, 38 and 10 gridpoints in the east, north and vertical directions, respectively. The horizontal resolution is Δx, Δy = 100km, which seems quite good, but the channel length is only 1200km in order to simulate small scale polar lows, so even east-west wave number 2 is reduced to a six grid interval wave. The channel is centered at 60°N with a Coriolis parameter of $1.25 \times 10^{-4}\ s^{-1}$ being used at the channel center.

This case produced a rapidly growing, shallow disturbance (somewhat deeper in the PE run) that reached a maximum EKE in 1.2 days for the PE, 1.8 days for the QG run, and then reached a relative minimum in EKE at 2.4 days for both runs. Thus, the life cycle occurs quickly, in 2.4 days. During the initial, linear stage of growth which lasts $\sim$ 1/2 day, the doubling time is $\sim$ 0.25 days. This is quite rapid development for both PE and QG models. The period of initial growth occurs by baroclinic conversion of potential to eddy kinetic energy; during the second part of the life cycle the eddy kinetic energy is converted to zonal kinetic energy. As in other cases, the PE model stabilizes the lowest portion of the channel (relative cooling of the buoyancy field at k=1, compared to the QG run; relative warming at k=2). As in most cases cited above and as in M82, the PE EKE reaches a maximum before the QG.

Table 3 presents a PE vs QG energetics comparison for the PL/CC case as well as for the other cases. The PE and QG energetics compare most poorly for the PL/CC case. This is due to the presence of the shallow layer of reduced stability in the basic state and due to the fact that the disturbances are very shallow. The stabilization process in the PE model significantly increases the lower level $\overline{B}^{xy}_{z}$ while this does not change for the QG model. This factor makes a major difference in computation of the ZAPE and the EAPE which is part of the EE (see Fig. 2, p 2420 in M82). Since the disturbances grown mainly in this shallow region, the effect is greatly magnified and hence the EE and ZAPE values differ so greatly in Table 3. Yet, as mentioned above, consideration of the EKE shows both PE and QG undergo life cycles of 2.4 days.

With respect to the zonally averaged fluxes of heat and momentum, the PE and QG structures are similar but they differ in magnitude. During the growth stage for both models, the heat fluxes are similar, being northward and shallow, with the QG flux roughly twice as strong as the PE flux. During this stage the momentum fluxes also are similar, being shallow and directed southward with the maximum being beneath the jet core. The PE momentum flux is about twice as strong as the QG flux.

During the decay phase of the life cycle the PE and QG fluxes are similar but they differ in relative strength. The heat fluxes remain quite shallow, but north of the region of northward heat flux there is a stronger region of southward heat flux. The QG flux during this stage is about three times stronger than the PE flux. The momentum fluxes during the decay stage are similar, remaining shallow with a convergence of flux beneath the jet core. Thus, both models produce a northward directed flux, north of which is a southward directed flux. In the QG model the southward directed region is twice as strong as the northward directed region while in the PE flux the northward directed region is a little stronger than the southward directed region. Both fluxes during the early decay stage are about the same strength but the QG flux becomes stronger as the PE flux weakens, so overall the QG flux is stronger. So the fluxes are similar in structure but different in magnitude over the life cycle.

Now consider the zonally and time averaged (over the 2.4 day life cycle) fluxes. Table 3 gives values. Like the weak front and no front cases, the time averaged heat fluxes are shallow and northward, but unlike the previous cases, for the PL/CC cases the QG heat flux is about four times the strength of the PE heat flux. The PE heat flux has a weak southward maximum at level k=5; the QG does not. The time averaged momentum fluxes are somewhat similar, but less similar than the heat fluxes, as was true for the front and no front cases. Both have a southward directed maximum at level k=1 and both have a secondary weaker southward directed maximum aloft. The QG momentum flux is about twice as strong as the PE flux.

The result of the action of the fluxes is that at the end of the life cycle the PE and QG zonally averaged buoyancy and zonal wind fields differ significantly at the lowest levels. For the zonally averaged zonal wind, the QG has developed a strong westerly jet at level k=1, nearly beneath the jet core. This westerly jet decreases in strength to level 2, above which the wind speed increases with height up to the jet core. This surface westerly jet is flanked by easterly jets. The PE zonal wind has a k=1 westerly component beneath the jet core, but it is less than half the strength of the QG k=1 westerly wind and the wind increases everywhere with height for the PE model. There are flanking easterly surface jets for the PE as for the QG model, but the QG easterly jets are stronger.

The zonally averaged buoyancy fields likewise are different at the lowest levels. The k=1 PE horizontal buoyancy gradient at the end of the life cycle is broader and weaker than at the start. The QG k=1 field has a relatively cold region south of a relatively warm region under the jet core. Thus the buoyancy increases northward at level 1 in the same region where the westerly wind decreases with height. A similar region does not appear in the PE field.

The PL/CC case produces a quite shallow disturbance growing mainly in a shallow region of reduced stability. The PE model stabilizes this region as the disturbance evolves while the QG model cannot, and the resulting QG/PE differences at the lowest levels are more pronounced in this case than in any of the other cases.

b. The 2-Wave case

In an attempt to increase the complexity of the basic states for PE/QG comparisons (and hence to increase the realism), I decided to attempt to model the upper tropospheric interaction of a shortwave propagating through a long wave. I could then model a jet streak (associated with a short wave trough) as it propagates downstream from the long wave ridge and around the long wave trough. Such situations seem to be associated with upper level frontogenesis (see Keyser and Pecnick, 1985, p. 1260, for example).

I decided to model this situation by adding two perturbations to a zonally independent basic state, both normal mode solutions found as previously described. The first perturbation (the long wave) had a wavelength equal to the channel length; the second (the short wave) had a wavelength equal to half the channel length (so two short waves are present initially). Waves 1 and 2 were added to the basic state in this manner.

A basic state, different than the "polar low" basic state discussed previously, needed to be chosen so that the following criteria were satisfied:

1) the short waves would grow more rapidly than the long wave,
2) the short waves would propagate eastward more rapidly than the long wave and
3) both long and short wave disturbance amplitudes would be relatively "deep," i.e., they would possess large disturbance amplitudes at jet stream level.

The third criterion hopefully allows deep surface frontal zones to form and favors more vigorous upper tropospheric activity including frontogenesis in the PE model runs.

After several modifications, a basic state was found that produced satisfactory results. It was similar in structure to I-N(0). The channel length was chosen to be 5200km (so waves 1 and 2 possessed 5200km and 2600km wavelengths, respectively), the width 6066 2/3km; with 26 gridpoints E-W and 30 N-S the grid resolution Δx, Δy = 216 2/3km, a coarse resolution, especially compared to the polar low simulations. Again 10 vertical levels were present.

Both perturbations were superimposed, with small amplitudes, on the zonally independent basic state: the maximum N-S perturbation wind component was set to be 10% of the maximum zonal basic state wind value. The initially small perturbation amplitudes allow the early growth and movement of the waves to be compared to linear theory. No "initial balancing" was included for the PE runs, instead, the initial wind and buoyancy fields were derived from the nondivergent stream function via the geostrophic and hydrostatic approximations, respectively, as is done routinely for the QG model.

Several runs were made, with and without friction for the PE model and all without friction by the QG model. We will discuss here only the frictionless PE and QG runs; a PE run with surface stress will be discussed below. For all these runs, the short wave troughs initially were located in the long wave ridge and trough. For both the PE and QG runs, the short waves propagated eastward relative to the long waves and short waves did indeed propogate through the long wave trough, on days 4 to 5 and again at approximately days 8 to 9. PE and QG runs with only the long wave and only the short waves also were carried out to shed light on the wave interactions in the 2-Wave runs.

These runs are being analyzed and papers are planned. A Masters thesis is being written based upon the short wave - long wave interactions occurring at days 4 and 5. What follows in this section will discuss the energetics and time averaged flux comparison for the PE and QG runs.

Both PE and QG runs proceed in a "growth" stage to about day 11. During that time, for both models the ZAPE and ZKE decrease while the EE increases. (See Table 3.) Thus, during this time the disturbances in the channel are growing both by the baroclinic and barotropic instability processes.

After day 11, a reversal occurs with EE decreasing while ZKE and ZAPE increase. This continues to day 14 in the PE model, thus a "life cycle" is observed in the PE energetics as described in M82. For the QG run the behavior is similar to the PE run after day 11 except no significant increase in ZAPE occurs and the EE does not decrease as much as in the PE run. Thus a decay stage is clearly seen in the PE model, less clearly in the QG model. During the entire 16 days of integration, the magnitudes of the PE and QG energy values are quite similar. Since two independent disturbances are present, the above says little about the individual disturbance life cycles.

The zonally averaged fluxes of heat and momentum have been time averaged over the growth stage, days 0-11. They are summarized in Table 4. During this time, the horizontal and vertical heat fluxes are quite similar for the PE and QG cases, with the QG fluxes being approximately 10% stronger. The horizontal momentum fluxes are similar, but not as similar as are the heat fluxes. Both have a flux divergence in the vicinity of the jet, indicative of the growth of the disturbances by barotropic as well as baroclinic instability. The vertical momentum fluxes are least similar, with the PE flux being downward everywhere while the QG flux is upward south of the channel mid-line and downward north of the mid-line. Thus, the flux behavior for the growth phase of the 2-Wave run is somewhat similar to that for the runs decreased in M82.

In summary, a comparison of the 2-Wave PE and QG runs show similar overall development. Details will be discussed in forthcoming papers.

B. PE runs only. Occluded frontogenesis study

The second major objective of this project was to study the formation of frontal cyclones and the dynamics of occluded frontogenesis. This requires a study of PE model output only. From archived data gotten from PE integrations run under this and earlier projects, 28 cases were available for study. These can be grouped into several categories:

1) Runs that are one wavelength zonally (only one disturbance present initially in the E-W cyclic channel), have no friction and begin with no surface front added to the basic state
2) As in 1) but an added weak E-W frontal zone present initially
3) As in 2) but possess some form of surface friction
4) As in 1) but have some form of surface friction
5) Runs that are more than one wavelength zonally (i.e. 2 or 3 disturbances present initially along the channel length), have no friction and begin with no surface front added to the basic state
6) As in 5) but surface friction is present.

Within these categories eight different basic states have been used, with varying channel lengths and disturbance structures. Except for the runs from my original Ph.D. thesis work that possessed 20 vertical levels (Δz = .75km), all these runs have 10 levels (Δz = 1.5km). This resolution is much too coarse to resolve any vertical structure in surface fronts that form, including occluded fronts. Even the 20 level runs do not show any vertical structure, so the classical picture of the warm occlusion or the cold occlusion cannot be investigated. What follows concerns for the most part the horizontal structure.

Consider first the runs possessing a weak initial frontal zone, categories 2) and 3) which include 4 cases. It was hoped that as a cyclone formed, this front would remain intact but would become progressively distorted, and the disturbance would form essentially as a frontal wave cyclone. In fact, as the front distorted into a wave, at the apex of the wave the vertical stability in the front and the negative relative vorticity on the cold side of the front decreased, so this region of the front lost frontal characteristics except for the buoyancy gradient remaining relatively large compared to north and south of the region. The buoyancy gradient becomes stronger in other regions of the front, especially in the friction runs. Thus, the effect of the front being present initially is minimal in the wave apex region as the wave amplifies.

We now turn our attention to the situations where no initial front is present in the basic state. Consider first the cases where only one east-west wavelength is present, i.e. only one disturbance is present in the channel. This covers categories 1) and 4) and includes 16 cases. Only 2 cases will be compared here; others will be considered in a forthcoming paper on occluded frontogenesis. We consider here two cases that possess relatively high resolution in some manner: a thesis run (called "T") with Δx, Δy = 100km and 20 levels in the vertical (38 east-west points, 62 north-south, 20 levels) and the fine resolution "PL/CC" run with Δx, Δy = 50km and only 10 levels in the vertical (26, 50, 10). The former contains no friction, the latter has surface stress present. Aspects of the former run are discussed in M74, section 5 (pp 873-878) while aspects of the latter are discussed in M87.

These situations are quite different yet similar characteristics are present with respect to the region we can regard as a forming "occluded front." The variables p and b for k=1 for day 4 for "T" are shown in Figs. 3E and 3F of M74, p 872; p and b for k=1 for day 1 for "PL/CC" are shown in Fig 3b of M87. Both runs are at somewhat similar stages of development; the warm, narrow tongue of air representing the center of an occluded region is present.

The vorticity is shown for these two cases, at the times above, in Figs 8A (M74, absolute vorticity, k=2) and Fig 4a (M87, relative vorticity, k=1). Both show a maximum region laying within the warm tongue, with relative minima laying on either side of this region, on the cold sides of the warm and cold fronts flanking the warm tongue. The vertical stability shown in Fig. 8B (M74, k=2) for run T, not shown for run PL/CC, has a similar pattern for the two runs; in the regions of the cold and warm fronts it is a relative maximum on the cold side and a relative minimum on the warm side of the fronts. In the warm tongue it is a minimum. Yet the region of minimum extends NW into the low center and there is no relative maximum of stability in either run NW in the region of the warm tongue. This is where the NW end of the "occluded front" would be and if it formed in the classical manner with the cold front "catching up" to the warm front we would expect to see "back to back" fronts with relatively stable regions on either side of the maximum vorticity and maximum buoyancy region. We can conclude that for these two cases the NW end of the occluded front does not show this structure although the b fields seem to suggest this has happened. (The occlusion is in the early stages for both these runs at these times; other cases have much longer "occluded front-like" b patterns at later development times.) The "horizontal frontogenesis function" $\frac{d}{dt} (\nabla_H b)^2$ is shown in Fig 6C (M74, p 876) for run T; it is not shown for run PL/CC but the pattern is similar: in the warm and cold front regions SE of the warm tongue the frontogenesis is a relative maximum (and in both cases is strongest in the short warm front). Yet in both cases in the northern portion of the warm tongue the function is negative; parcels moving through this region are experiencing frontolysis. What appears to be happening is that within the high vorticity regions the warm air has been advected northward, creating the appearance of an occluded front region, but no frontogenesis has occurred. The cold front has not "caught up" to the warm front. In both of these runs the warm front has formed first and the cold front is forming even as the occlusion region is developing. Other runs have different variations on this; a forthcoming paper on occluded frontogenesis will discuss the results.

Finally in this section we turn to the cases where more than one disturbance appears east-west in the channel. This allows for greater realism in that the disturbances can be different from one another, while the "one disturbance in a channel" cases effectively represent an infinite chain of the same disturbance, due to the cyclic boundaries. We will comment on one of these cases here. This was mentioned above as a "third attempt - a frontal cyclone." This was a 2-Wave PE run with surface stress; after day 7 a frontal cyclone evolved as a pre-existing cold front. It was the only example of such a development in this work. Unfortunately, the resolution is quite coarse (Δx, Δy = 216 2/3km, 10 levels in the vertical) but the development is interesting and seems more like the classical occlusion process than the previous cases. The cold front does seem to "catch up" to the warm front. Yet in the northern region of the cold front, where it has paralleled to the warm front and forms the "back half" of the occluded front, frontolysis is occurring similar to the above cases. This case also will be discussed in the "occluded frontogenesis" paper.

Another aspect of the friction runs concerns the type of friction used. For most of the runs only a surface stress type of friction was present (discussed in M87). This was done because, with 10 levels, level k=2, at 2.25km, is above the top of the typical boundary layer. But having friction only as a drag term at level 1 uncouples the lowest layer somewhat; in some of the cases the warm tongue at k=1 undercuts the k=2 development and the stability $\frac{\partial b}{\partial z}$ becomes negative in the region. So vertical mixing was added to the friction, as described in Appendix A in M87. This effectively deepens the boundary layer but it couples levels 1 and 2 more than in the surface stress only formulation. The I-N(0) run was repeated with this more complete form of friction, so that the two forms of friction could be compared to each other and to I-N(0) with no friction. The "occluded frontogenesis" paper will comment on the effect of the different formulations of friction on the occlusion process.

C. Summary of the results

To a large extent the results of the PE/QG comparisons in this project are similar to those discussed in M82, since the cases used here are similar to those used in M82. That is to say the QG runs simulate the PE cases in many respects. 1) The PE cyclone wave evolutions stabilize the lower troposphere while the QG evolutions cannot. 2) Both PE and QG cyclones evolve through a life cycle with the QG cycle generally lasting longer, and 3) The QG life cycle averaged eddy heat fluxes are similar to the corresponding PE fluxes. The heat fluxes generally are more similar (PE vs QG) than are the momentum fluxes. All the above are in agreement with the M82 results.

There is, however, a greater diversity in the results, given a greater diversity in the basic states chosen. In some cases, the QG fluxes are larger than the corresponding PE fluxes; in other cases the situation reverses. In M82, the PE fluxes were larger than the QG fluxes. In one case (I-N(0)FZ), the QG model does a better job of simulating the PE run than for the corresponding M82 case (I-N(0)). On the other hand, for the PL/CC case the QG model does more poorly in simulating the PE run, compared to other cases. For a case where the basic state apparently is stable, both PE and QG display no significant growth of the superimposed perturbation.

We must conclude that as the diversity of cases grows, the QG simulations of the PE runs must be expected to become more varied.

With respect to the attempt to model the formation of occluded fronts in maturing cyclones using the PE model, given the very limited vertical resolution, too coarse to describe the frontal scale, our results are valid only with respect to the horizontal structure of the fronts. Even the horizontal resolution is quite coarse. The buoyancy (temperature) patterns (not shown) suggest the cold front "catches up" to the warm front and a narrow tongue of warm air is trapped in between. Yet examination of the vorticity, vertical stability and frontogenesis function in the vicinity of the "occluded front" suggest the warm tongue is advected toward the cyclone center and the northern end of the cold front undergoes frontolysis during this process. A paper is planned on this subject.

D. Implications of the results

At the beginning of M82 a discussion of "climate forecast" models appeared. It was pointed out that the success of such long range models "will partially depend on the ability to simulate or "parameterize" the effect upon the surrounding atmosphere of the day to day evolution of cyclone waves, which cannot be predicted to any degree of accuracy." A run of weather associated with a given climate forecast probably will include the growth and decay of cyclone waves of varying sizes and strengths. More than one event will probably be occurring at a given time. It was therefore suggested in the proposal for this project that the validity of QG dynamics vis-a-vis PE dynamics should be investigated for a variety of situations. As stated in the proposal, "If the QG model is found to simulate in a satisfactory way different types of situations expected in a sequence of weather, we would feel more confident about using QG dynamics to build parameterization schemes or statistical methods to simulate the combined effect of such situations." Conversely, if situations are found where the QG model does a poor job in simulating PE model runs, our confidence would drop.

We have added diversity to the PE/QG cases used here over those in M82. We have found more diversity in the results. This suggests that, in the context described above, our confidence in the ability of QG dynamics to simulate the PE dynamics should decrease.

In a similar study, MacVean and James (1986) stress the differences in the PE and QG eddy momentum fluxes in the latter portion of the baroclinic wave life cycle. They feel that QG dynamics may not be adequate for parameterization of cyclone waves in PE "climate" models. Based on my overall results, the I-N(O)FZ case not withstanding, I must concur with MacVean and James (1986). It may be possible to use QG dynamics for the above stated purpose, but these results suggest it will be more difficult than I previously thought.

6. References

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BASIC STATE	CHANNEL WIDTH D $\times 10^3$ KM	JET WIDTH D_J $\times 10^3$ KM	WIND SPEED AT JET CENTER U_0	U_M	U_T	TROPOPAUSE HEIGHT $H_T(Y_0)$	$H_T(Y_J)$	$H_T(Y_1)$	MINIMUM RICHARDSON NUMBER $R_{iT\,MIN}$ TROP	$R_{iS\,MIN}$ STRAT	MERIDIONAL TEMPERATURE CHANGE TROP	STRAT	Y_0	Y_J	Y_1	STATIC STABILITY $\times 10^{-4} S^{-2}$ N_T^2 TROP	N_S^2 STRAT
			MS^{-1}			KM					°C		$\times 10^3$ KM				
I-N(0)	4.2	2.0	0	40	30	11.5	10.5	9.7	9.0	93.2	12	-7	1.1	2.1	3.1	1.3	4.6
I-N(0) FZ	4.2	2.0	-5.1* 8.4	40	30	11.5	10.5	9.7	14.5	93.2	12	-7	1.1	2.1	3.1	1.3	4.6
PL/CC	3.6	2.0	0	75	56	13.8	10.0	8.9	2.4** 0.5	37.7	26	-28	0.8	2.13	2.8	1.3 0.29**	5.3
2-WAVE	6.067	2.0	0	40	30	10.7	10.0	9.4	5.7	135.4	12	-6	2.03	3.03	4.03	0.92	5.4

TABLE 1. BASIC STATES. SEE FIG. 1, M82 FOR EXPLANATION. FOR ALL CASES, CHANNEL DEPTH $H = 15$ KM, $f_0 = 1 \times 10^{-4} S^{-1}$ EXCEPT PL/CC $f_0 = 1.25 \times 10^{-4} S^{-1}$. $K = (U_T/U_M) = 0.75$ AND $U_T = U(Y = Y_J, Z = 1)$. $R_{iT} = N_T^2 [H_T(Y_J)]^2 / (U_M - U_0)^2$, $R_{iS} = N_S^2 [15 - H_T(Y_J)]^2 / U_M^2 (1-K)^2$. TEMPERATURE INCREASES TOWARD NORTH IN STRATOSPHERE. SUBSCRIPTS S AND T ON R_i AND N^2 REFER TO STRATOSPHERE AND TROPOSPHERE, RESPECTIVELY.

* I-N(0) HAS $U = 2.9\ MS^{-1}$ AT ($j = 15 + 16$, $k = 1$), I.E. AT $Z = 0.75$ KM. FOR I-N(0)FZ AN EASTERLY MAX OF $-5.1\ MS^{-1}$ IS AT ($j = 11$, $k = 1$), A WESTERLY MAX OF $8.4\ MS^{-1}$ IS AT ($j = 16$, $k = 1$).

** FOR PL/CC, N_T^2 OF LOWEST 3 KM IS LESS THAN N_T^2 FOR REMAINDER OF TROPOSPHERE, SO IS MIN R_i.

RUN		HORIZONTAL RESOLUTION			HORIZONTAL DOMAIN		VERTICAL RESOLUTION		TOTAL # OF GRIDPOINTS	INITIAL AMPLITUDE	TIME-STEP ΔT	DURATION OF INTEGRATION	GROWTH RATE (LIN. QG THEORY)	DOUBLING TIME	END OF FIRST LIFECYCLE
		# OF GRDPTS E-W	# OF GRDPTS N-S	$\Delta X = \Delta Y$ KM	CHNL LENGTH L KM	CHNL WIDTH D KM	# OF GRDPTS	ΔZ KM		%	MIN	DAYS	DAY^{-1}	DAYS	DAY
I-N(0)	PE QG	26	30	150	3600	4200	10	1.5	7800	10	10 40	15+ 22	.718	.965	8 14
I-N(0) F2	PE QG	26	30	150	3600	4200	10	1.5	7800	10	10 40	11 3/4 22	.473	1.47	10 14
PL/CC	PE QG	14	38	100	1200	3600	10	1.5	5320	5	4 16	5.6 11.2	2.75	0.252	2.3 2.3
2-WAVE	PE QG	26	30	216 2/3	5200	6066 2/3	10	1.5	7800	10	10 40	16 16	* .735 (.557)	* .943 (1.25)	14 15

TABLE 2. CHARACTERISTICS OF MAJOR INTEGRATIONS.

* ( ) VALUES ARE FOR LONG WAVE, OTHER VALUES ARE FOR SHORT WAVES IN 2-WAVE RUN.

RUN		EDDY ENERGY EE = EAPE + EKE				ZONAL AVAILABLE POTENTIAL ENERGY ZAPE					ZONAL KINETIC ENERGY ZKE				
		DAY OF MAX	MAX $\times 10^{-4}$	DAY OF MIN	$\frac{MIN}{MAX}$	INITIAL $\times 10^{-4}$	DAY OF MIN	MIN $\times 10^{-4}$	DAY OF MAX	MAX $\times 10^{-4}$	INITIAL $\times 10^{-4}$	DAY OF MIN	MIN $\times 10^{-4}$	DAY OF MAX	MAX $\times 10^{-4}$
I-N(0)	PE	4.6	2.35	7.7	0.36	4.09	5.3	2.65	7.7	2.88	3.69	4.0	2.57	7.8	3.82
	QG	6.4	3.30	14.1	0.30	4.10	7.5	2.13	14.8	3.46	3.71	4.8	2.11	13.0	3.25
I-N(0) FZ	PE	6.25	2.82	10.3	0.20	3.88	6.8	2.52	10.0	2.70	3.71	6.0	2.09	10.5*	4.18
	QG	6.25	3.18	13.8	0.44	4.01	7.0	2.32	14.8	3.32	3.78	6.0	2.04	13.0	2.94
PL/CC	PE	1.2	0.57	2.4	0.53	180.6	1.2	27.9	2.2	29.9	14.6	0.2	14.4	1.2	14.7
	QG	1.8	33.7	2.4	0.69	173.3	1.8	139.3	2.2	144.8	14.8	1.4	14.7	2.2	15.3
2-WAVE	PE	11.0	2.06	14.3	0.66	3.03	11.5	1.30	14.3	1.70	1.22	10.8	0.44	14.3	0.72
	QG	11.8	2.19	15.3	0.88	3.03	12.3	1.20	13.0**	1.21	1.28	11.0	0.56	16.0	0.92

TABLE 3. SUMMARY OF GROSS ENERGETICS. MAX, MIN MAY BE RELATIVE MAX AND MINS. VALUES ARE NON-DIMENSIONAL.

* SLOW INCREASE THEREAFTER

** DECREASE THEREAFTER

RUN		AVERAGING PERIOD DAYS	$\overline{b'v'}$ °C MS^{-1} LOWER (J,K)	$\overline{b'v'}$ °C MS^{-1} UPPER	$\overline{b'w'}$ °C MS^{-1} LOWER	$\overline{b'w'}$ °C MS^{-1} UPPER	$\overline{u'v'}$ M^2S^{-2} LOWER	$\overline{u'v'}$ M^2S^{-2} UPPER	$\overline{u'w'}$ M^2S^{-2} LOWER	$\overline{u'w'}$ M^2S^{-2} UPPER
I-N(O)	PE	0-8	9.7 (15,1)	-3.5 (20,8)	.0078 (15,2)	-.0024 (16,7)	-16.6 (17,1)	-10.8 (14,7)	—	-.018 (14,6)
	QG	0-14	4.7 (16,1)	-2.4 (16,8)	.0030 (15,2)	-.0025 (15,6)	2.8 (9,1)	-4.3 (11,8)	.0022 (10,4)	-.0036 (20,7)
I-N(O) F2	PE	0-10	7.8 (12,1)	-4.1 (19,8)	.0074 (13,2)	-.0027 (11,6)	-16.2 (17,1)	-17.8 (14,7)	—	-.023 (14,6)
	QG	0-14	4.7 (12,1)	-2.6 (18,8)	.0035 (13,2)	-.0017 (19,6)	-7.5 (14,1)	-6.3 (13,7)	-.0053 (13,6)	-.0059 (20,7)
PL/CC	PE	0-2.4	7.3 (18,1)	-1.8 (25,5)	.098 (23,2)	-.020 (21,3)	-29.0 (22,1)	-16.4 (23,4)	—	-.20 (23,5)
	QG	0-24	26.6 (20,1)	—	.182 (19,1)	—	-51.4 (21,1)	-21.7 (23,3)	-.23 (23,1)	-.21 (23,3)
2-WAVE	PE	0-11*	11.1 (14,1)	-1.2 (13,10)	.012 (15,3)	-.0033 (16,8)	-9.6 (15,1)	-12.5 (13,7)	—	-.018 (13,6)
	QG	0-11*	12.2 (15,1)	-1.5 (18,8)	.013 (15,2)	-.0018 (18,8)	—	-15.0 (12,8)	.010 (12,2)	—

TABLE 4. COMPARISON OF PE AND QG TIME AVERAGED EDDY FLUXES. FLUXES ARE ALSO ZONALLY AVERAGED. (J,K) REFERS TO GRIDPOINT LOCATION IN N-S VERTICAL CROSS SECTION OF RELATIVE MAX OR MIN GIVEN.

* GROWTH STAGE ONLY FOR 2-WAVE, OTHER RUNS AVERAGED OVER COMPLETE LIFE CYCLE.